



# ASPIRE Aerodynamic Models and Flight Performance

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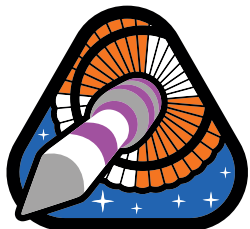
Jet Propulsion Laboratory, California Institute of Technology

John Van Norman

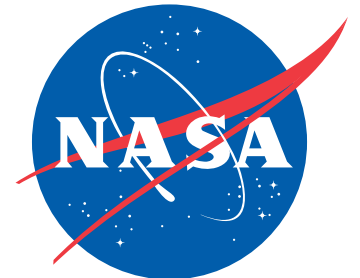
AMA Inc., NASA Langley Research Center

Ian Clark

Jet Propulsion Laboratory, California Institute of Technology

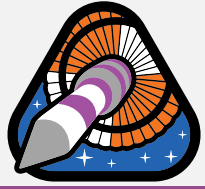


**ASPIRE**



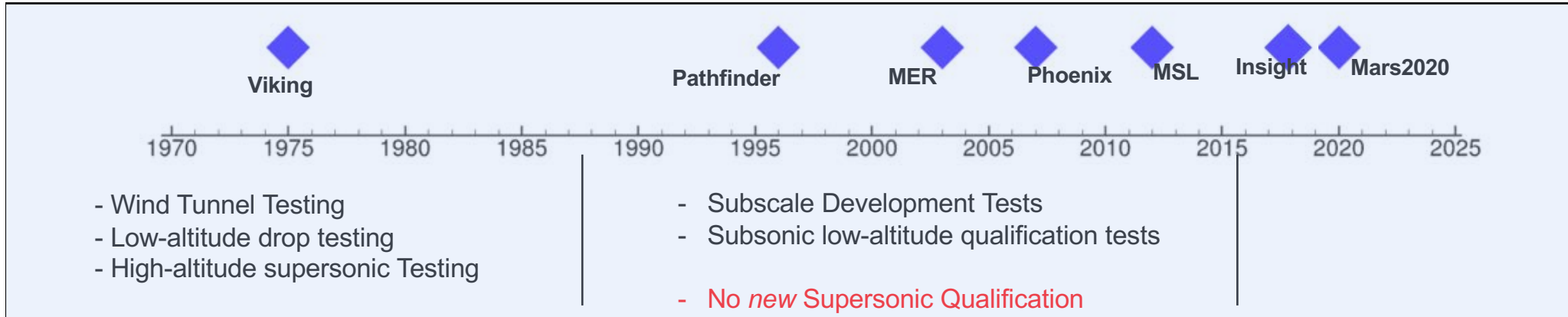
AIAA Aviation Forum, Dallas, TX, June 19<sup>th</sup> 2019

# Introduction



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- Disk-Gap-Band (DGB) parachutes have been used on all US Mars missions.
- All of the parachutes have been variants of the Viking DGB parachute.

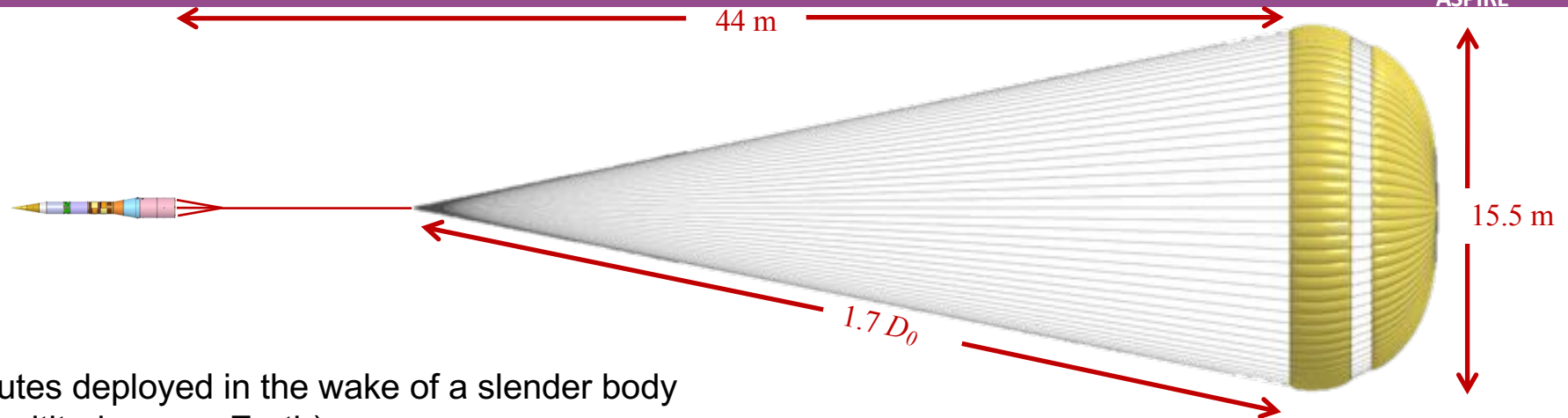
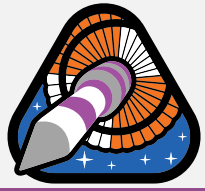


- Since Viking era,
  - Parachute materials have changed (Dacron → Kevlar, Nylon)
  - Analysis methods have evolved
  - Parachute size and load have increased
  - Design Margins have decreased
- Relationship between subsonic testing and supersonic flight performance is not clear



The [Advanced Supersonic Parachute Inflation Research and Experiments \(ASPIRE\)](#) project is tasked with deployment and testing of full-scale *Disk-Gap-Band* parachutes at Mars relevant conditions

# ASPIRE Test Architecture



- Parachutes deployed in the wake of a slender body (at high altitudes over Earth).
- Two candidate parachutes tested (same geometry, different materials and construction).
- The parachute will be used at Mars behind a blunt body (*Mars2020, estimated entry at Mars February 2020*).

ASPIRE Disk-Gap-Band (DGB) Parachute

- Reference Diameter ( $D_0$ ) 21.5 m
- Inflated Diameter 15.5 m

*Dimensions similar to MSL parachute*

Test	Parachute	Parachute Inflation load	Inflation Mach Number	Dynamic Pressure
SR01 (Oct 2017)	MSL	32,400 lbf	1.77	495 Pa
SR02 (Mar 2018)	Mars2020	55,800 lbf	1.97	626 Pa
SR03 (Jul 2018)	Mars2020	67,400 lbf	1.85	1020 Pa

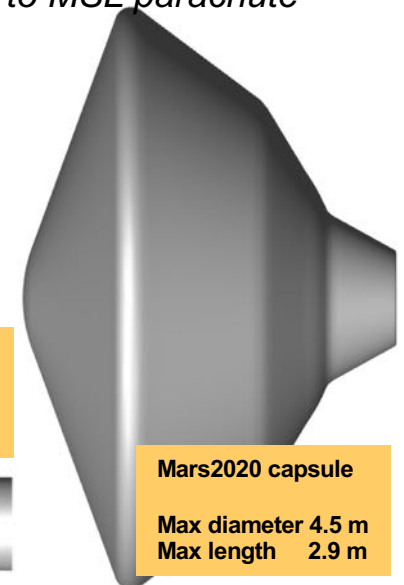
**Nominal predicted parachute load during Mars2020 entry: 35,000 lbf**

ASPIRE payload

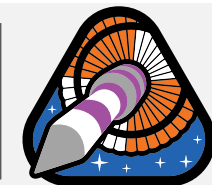
Max diameter 0.74 m  
Max length 6.6 m

Mars2020 capsule

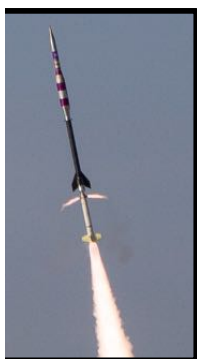
Max diameter 4.5 m  
Max length 2.9 m



# ASPIRE Flight Test



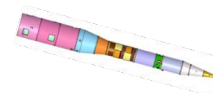
ASPIRE



**Payload Sep**  
L+104.045 s  
Alt: 49.92 km  
Mach: 1.27



**Apogee**  
L+119.1 s  
Alt: 51.0 km  
Mach: 1.19



**Mortar Fire**  
L+161.4 s  
Alt: 42.43 km  
 $q_{\infty}$ : 450.3 Pa  
Mach: 1.77



**Line Stretch**  
MF+0.961 s  
 $q_{\infty}$ : 490 Pa  
Mach: 1.79



**Peak Load**  
MF+1.47 s  
 $q_{\infty}$ : 500.0 Pa  
Mach: 1.79

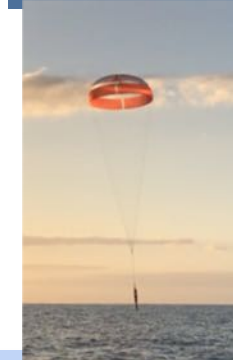
**2<sup>nd</sup> stage Brant burnout**  
L+35.1 s  
Alt: 16.7 km  
Mach: 3.34

**2<sup>nd</sup> stage Brant Ignition**  
L+8.16 s  
Alt: 1.564 km

**1<sup>st</sup> stage Terrier burnout**  
L+5.2 s  
Alt: 0.796 km



**Splashdown**  
L + 34 min



Atlantic Ocean

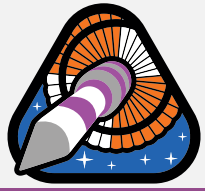
Launch Site  
(WFF, VA)

54.9 km

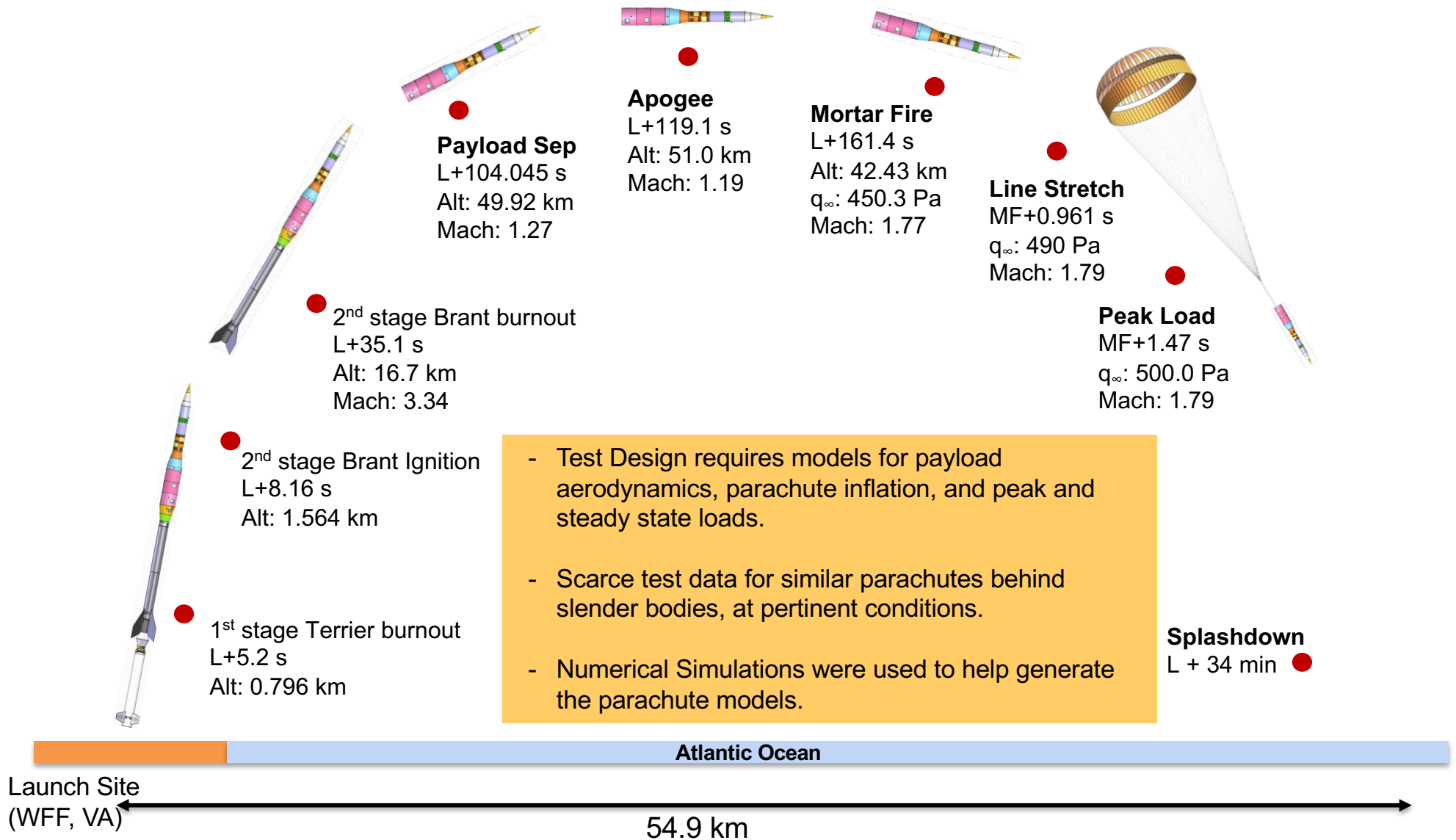
Thursday @ 11:00 AM:  
211-ADS-12: Summary of ASPIRE Sounding  
Rocket Tests with a Disk-Gap-Band Parachute

*Note: The numbers indicate actual quantities from first flight test (SR01), Oct 2017.*

# ASPIRE Flight Test



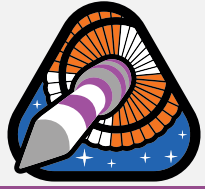
ASPIRE



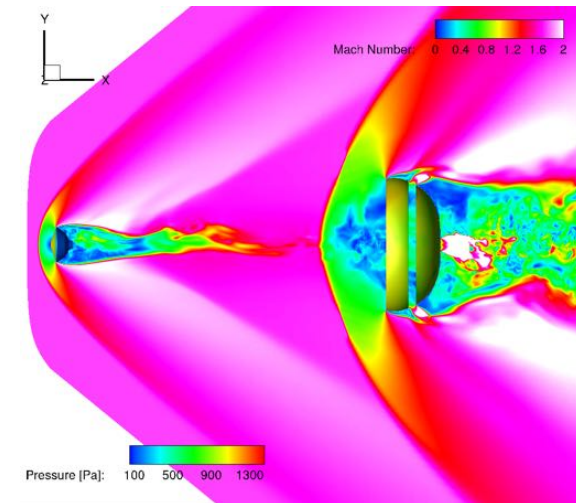
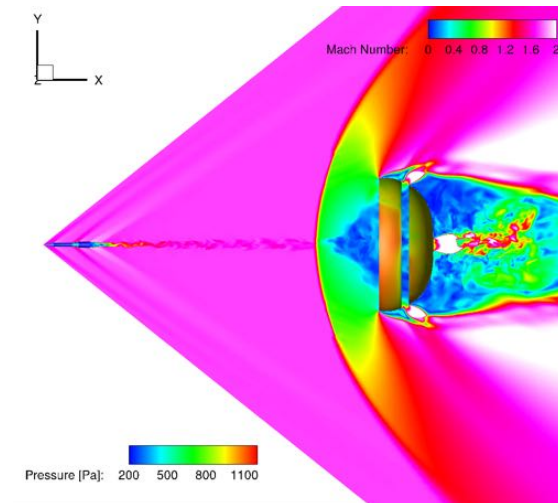
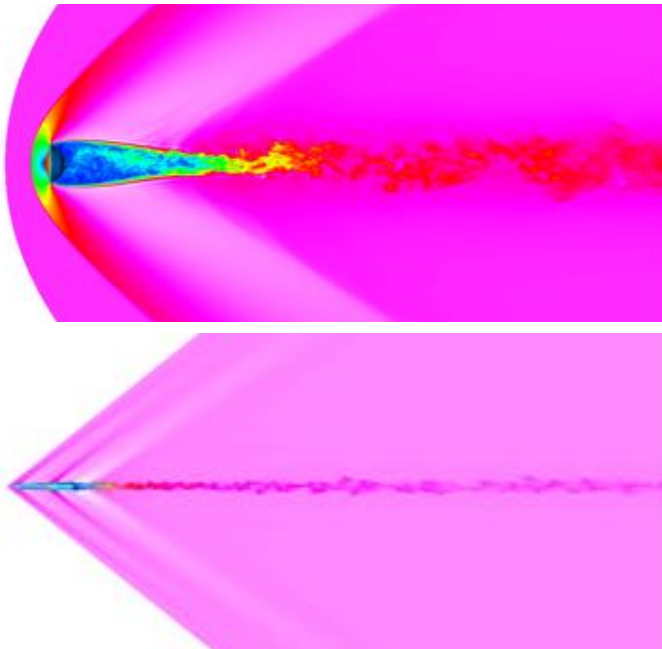
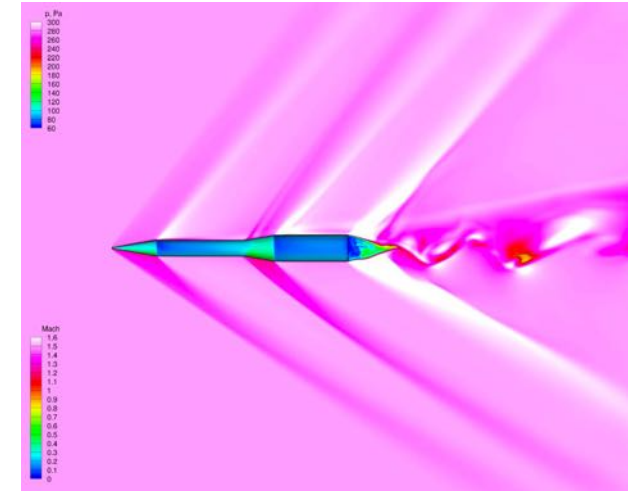
Objective: Present the Aerodynamic Models used for flight test design, and compare performance against test data



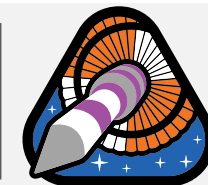
# CFD towards Flight Test Design



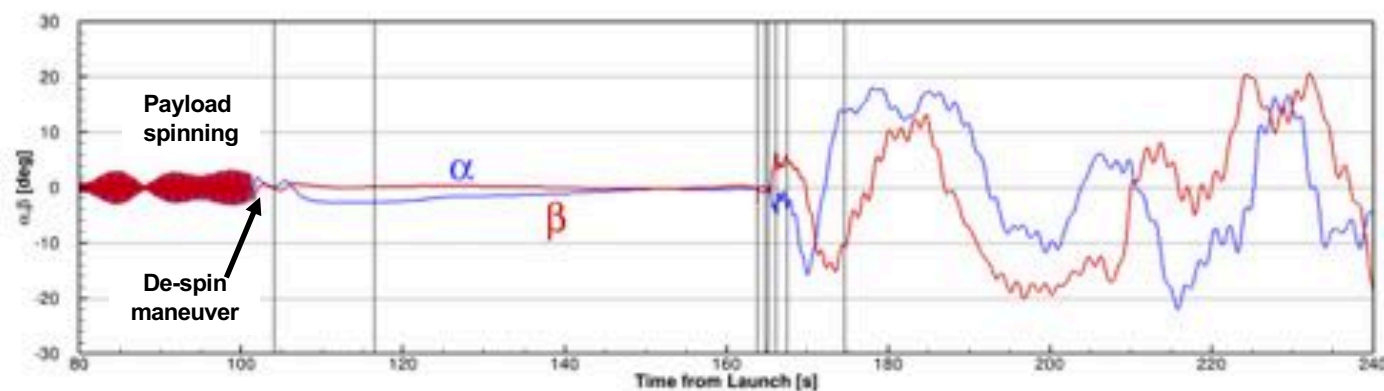
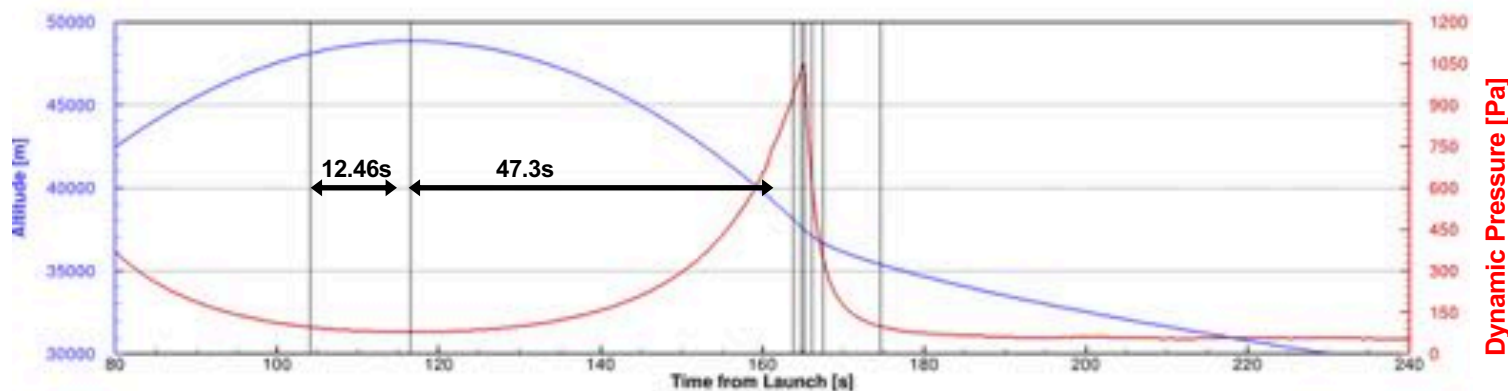
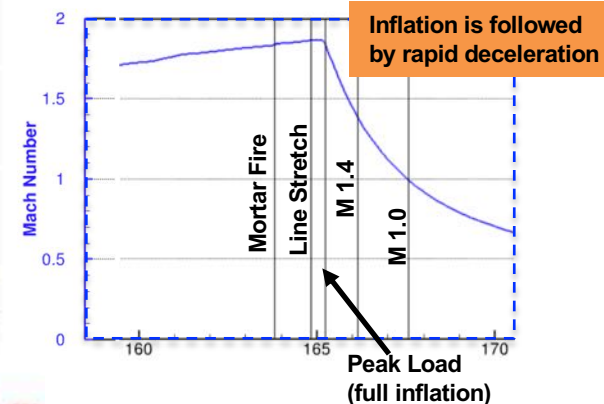
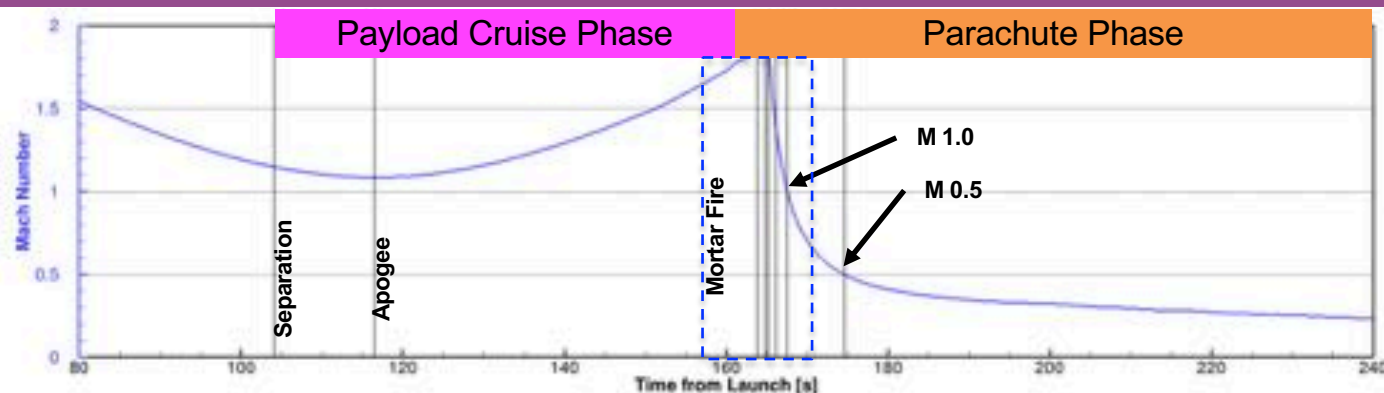
- Slender Body Simulations - to generate payload aerodynamic database.
- Wake Simulations - to explore blunt vs slender body differences, help with targeting during the flight test.
- Rigid Parachute Simulations - to investigate effect of leading body in parachute drag, generate pre-flight parachute drag model.
- Simulations in  $\text{CO}_2$  - to extrapolate parachute performance over Earth and predict performance at Mars.



# SR03 Flight Trajectory

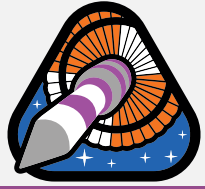


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<b>Payload Separation</b>	Altitude	48.1 km
	Dynamic Pressure	96.4 Pa
	Mach Number	1.17
	Velocity	372.5 m/s
<b>Apogee</b>	Altitude	48.85 km
	Dynamic Pressure	79.36 Pa
	Mach Number	1.11
	Velocity	354.8 m/s
<b>Mortar Fire</b>	Altitude	38.12 km
	Dynamic Pressure	931.74 Pa
	Mach Number	1.85
	Velocity	575.8 m/s
<b>Peak Parachute Load</b>	Altitude	37.46 km
	Dynamic Pressure	1020.0 Pa
	Mach Number	1.85
	Velocity	573.18 m/s

# Payload Aerodynamics Models



ASPIRE

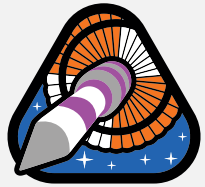
- Objective: To generate a Payload Aerodynamics Database to predict flight characteristics and performance
  - This model is used from the payload separation stage to the mortar-fire leading up to parachute deploy.
- Process: CFD Simulations of flow past the payload geometry at various conditions (freestream, angle of attack)
- Tools: OVERFLOW, DPLR, FUN3D
- Laminar and Turbulent flow calculations
- Product(s) :
  - Tables of static aerodynamic coefficients as a function of Mach number and angle of attack
  - Uncertainties in the static aerodynamic coefficients (applied as dispersions in the flight mechanics simulations)
- Challenges:
  - Long, slender body → significant viscous contributions (sensitivity to computational mesh and turbulent flow modeling)
  - Laminar-to-Turbulent transition criteria is not easy to implement (too many variables, not enough information on the pertinent geometry and the pertinent conditions)
- Approach:
  - Use both the laminar and turbulent flow simulations and aerodynamic behavior
  - Design a nominal based on the average ; use the differences to inform uncertainty

Mach	alt, m	T, K	$\rho$ , kg/m <sup>3</sup>	V, m/s	p, Pa	q, Pa	Re/m
0.900	57848	254.9	4.330E-04	288.0	31.68	17.96	7.677E+03
1.100	55605	264.0	5.585E-04	358.2	42.32	35.84	1.198E+04
1.500	49450	271.0	1.228E-03	495.0	95.50	150.4	3.564E+04
2.444	39265	258.6	4.900E-03	787.9	363.7	1521	2.350E+05

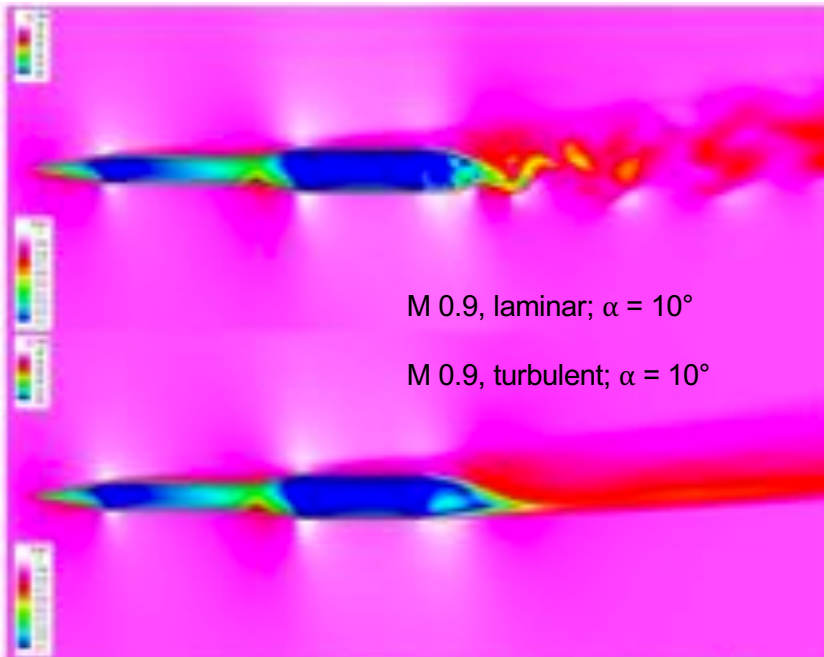
$\alpha_T = 0, 2, 5, 10, 15, 20, 30, 45, 60, 75^\circ$



# Payload Flow Visualization

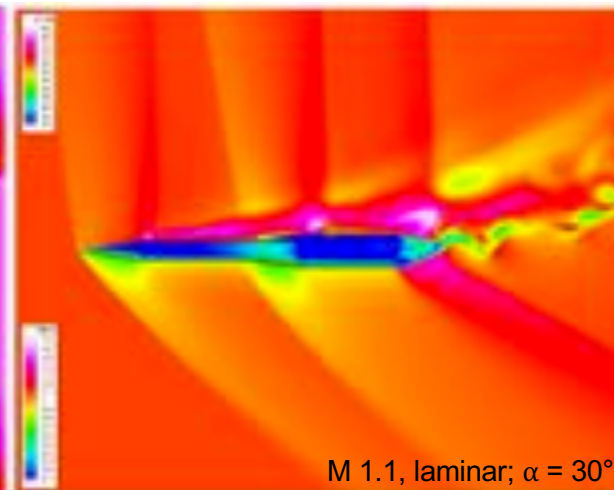


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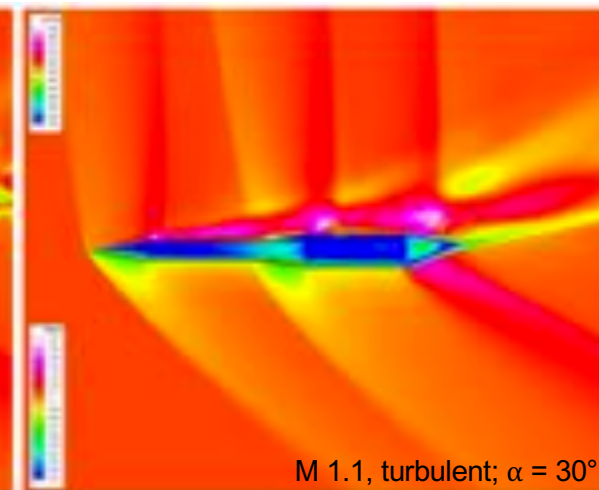


M 0.9, laminar;  $\alpha = 10^\circ$

M 0.9, turbulent;  $\alpha = 10^\circ$



M 1.1, laminar;  $\alpha = 30^\circ$



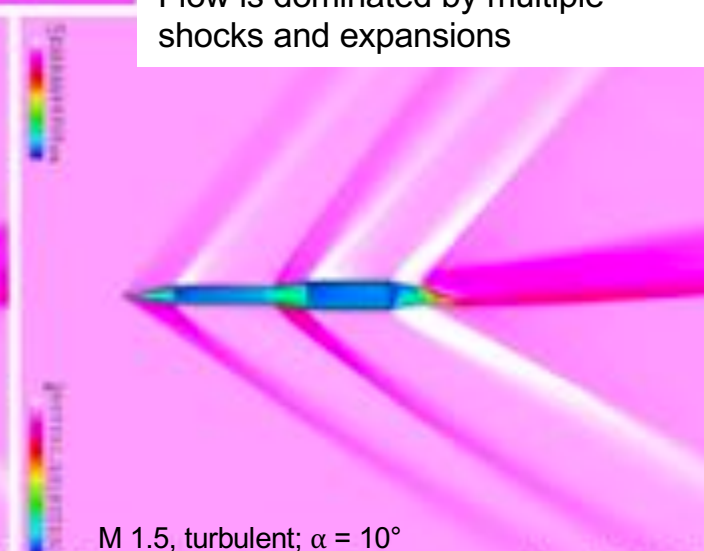
M 1.1, turbulent;  $\alpha = 30^\circ$

Payload length: 6.0 m  
Payload diameter: 0.74 m

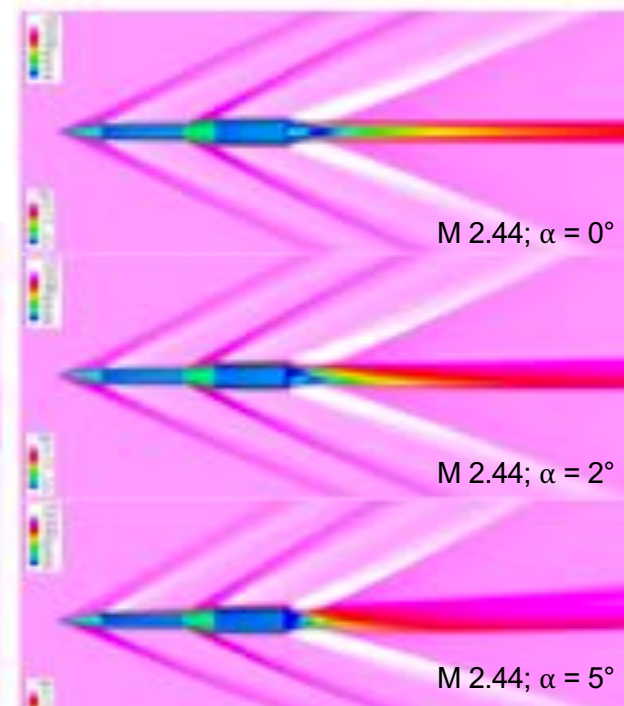
Flow is dominated by multiple  
shocks and expansions



M 1.5, laminar;  $\alpha = 10^\circ$



M 1.5, turbulent;  $\alpha = 10^\circ$

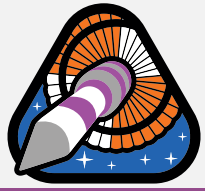


M 2.44;  $\alpha = 0^\circ$

M 2.44;  $\alpha = 2^\circ$

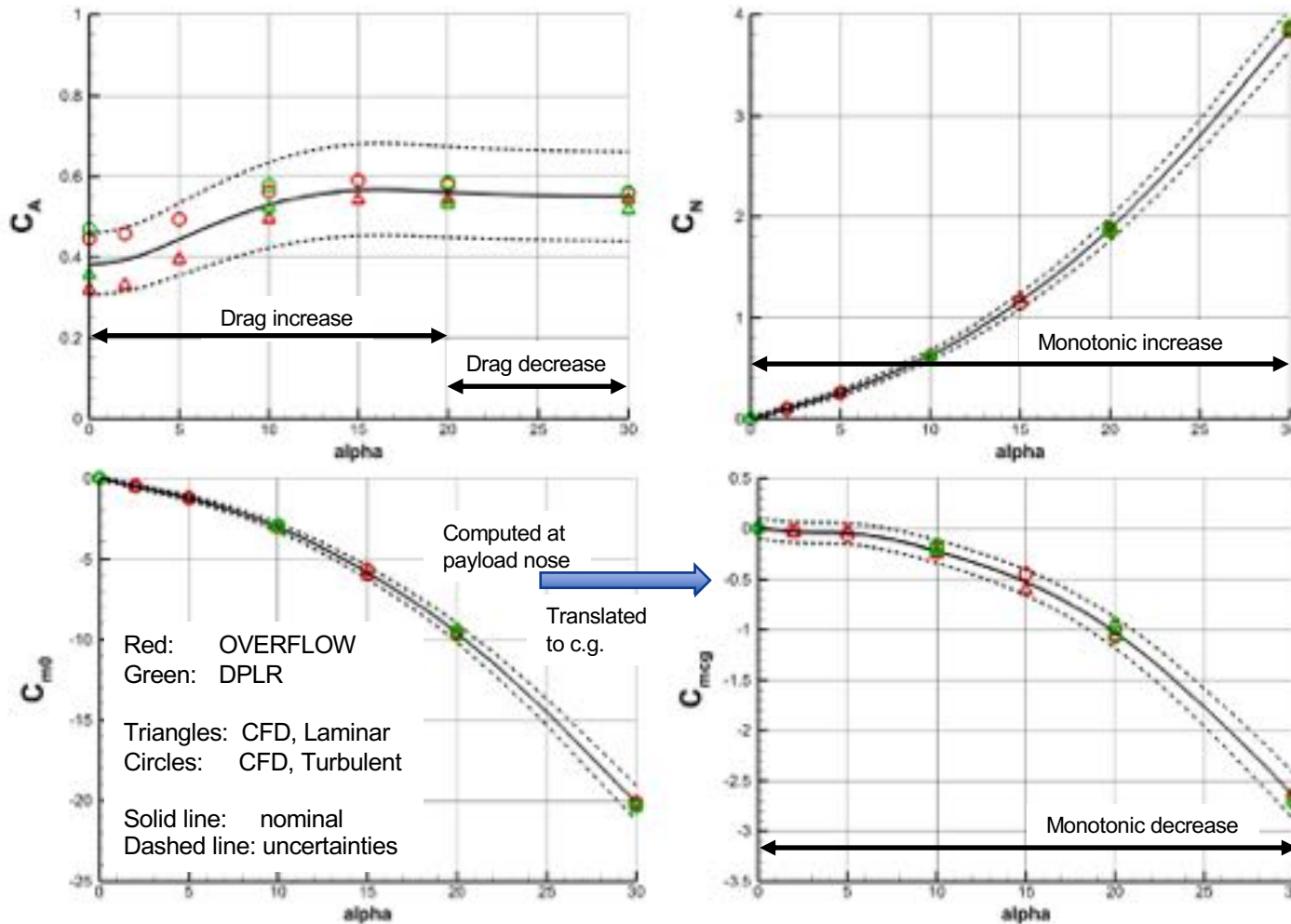
M 2.44;  $\alpha = 5^\circ$

# Payload Aerodynamic Model

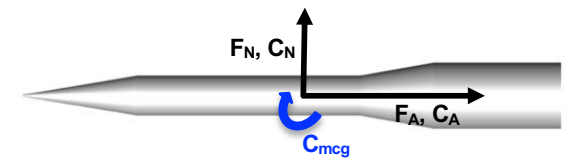


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## Freestream Mach number 1.5

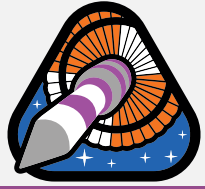


- Plots show variation of aerodynamic force/moment coefficients as a function of angle of attack
- In general, there is a reasonable agreement between solutions from different solvers
- There is a larger difference between laminar and turbulent flow
- Nominal curves are based on averages ; uncertainties are informed by the differences.



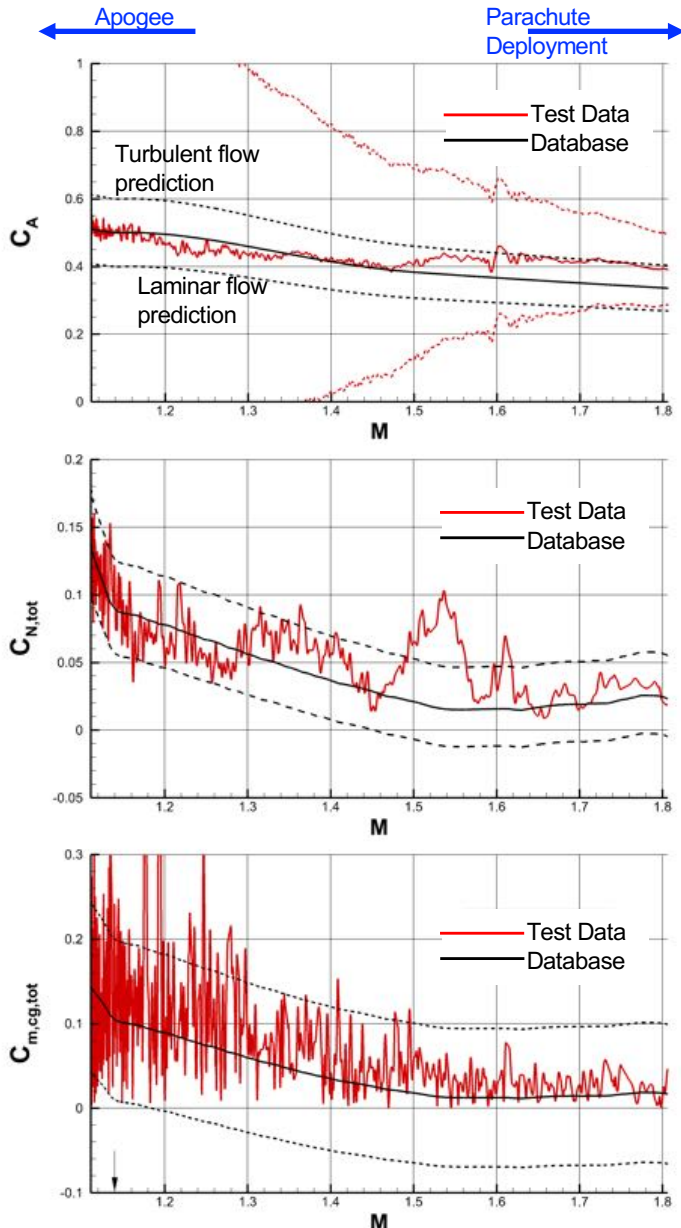
Data at multiple Mach numbers, so generated, is used by flight mechanics simulations, and to design the flight test

# Post-Flight Reconstruction



ASPIRE

SR03 Flight data



On-board IMU  
Atmospheric Model  
GPS, and RADAR

Trajectory  
(linear & angular  
accelerations)

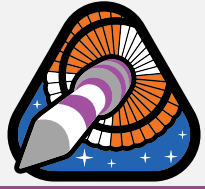
Payload  
Aerodynamics

- Payload coast phase: from payload separation to parachute deploy (high altitude, low density and dynamic pressure, lower aerodynamic forces and measured accelerations)
- Challenge: Measured accelerations are of the order of the *resolution* of the IMU (sized to measure forces during parachute deployment).
- Uncertainty in reconstructing aerodynamic coefficients exceeds the coefficients themselves.
- Comparisons show:

*Validates design process*

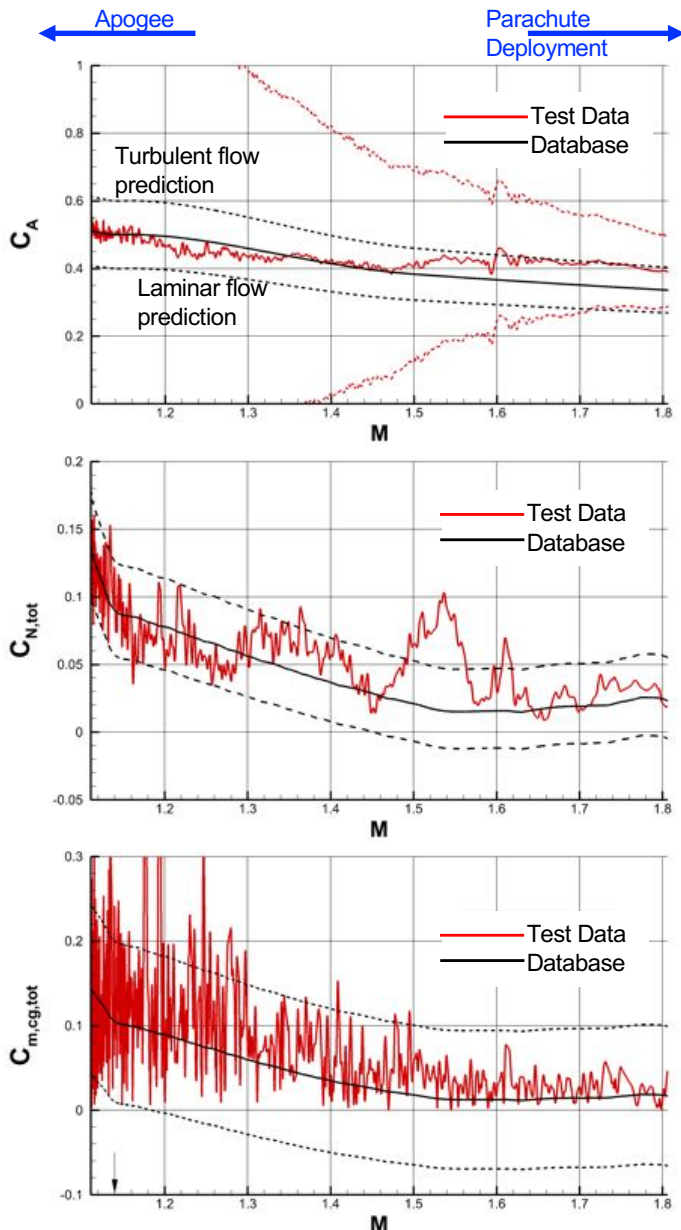
- Flight data falls within the pre-flight bounds
- Nominal flight data compares reasonably with pre-flight predictions
- In general, flight data closer to turbulent flow predictions than laminar flow predictions (particularly as the velocity increases).

# Payload Aerodynamics Reconstruction

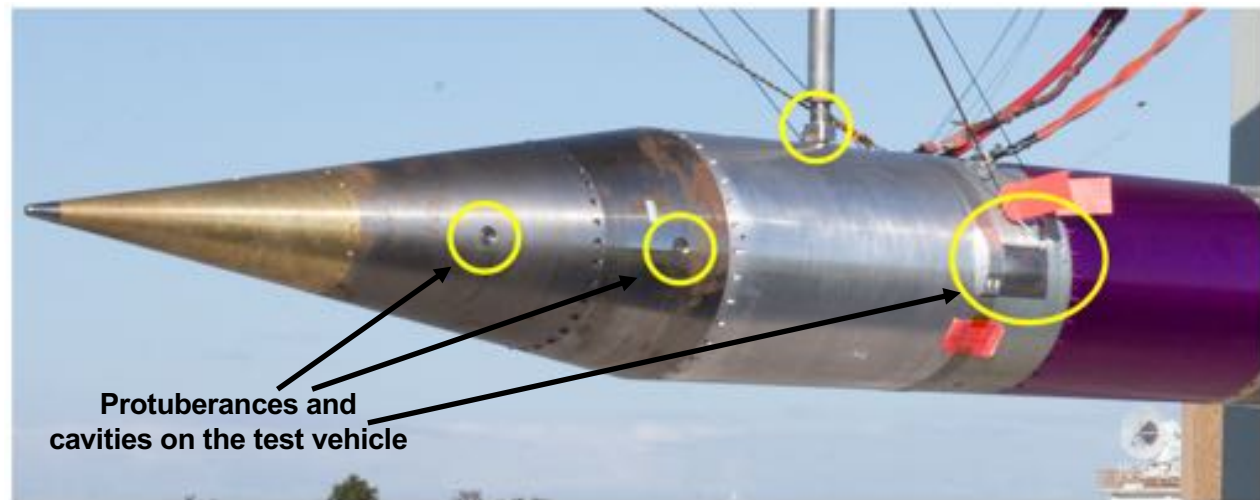


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## SR03 Flight data



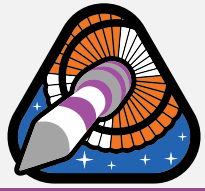
Pre-flight database assumes a smooth geometry ;  
Vehicle surface contains non-smooth features → flow is likely to trip



- Comparisons show:
  - Flight data falls within the pre-flight bounds
  - Nominal flight data compares reasonably with pre-flight predictions
  - In general, flight data closer to turbulent flow predictions than laminar flow predictions (particularly as the velocity increases).



# Parachute Aerodynamic Models



ASPIRE

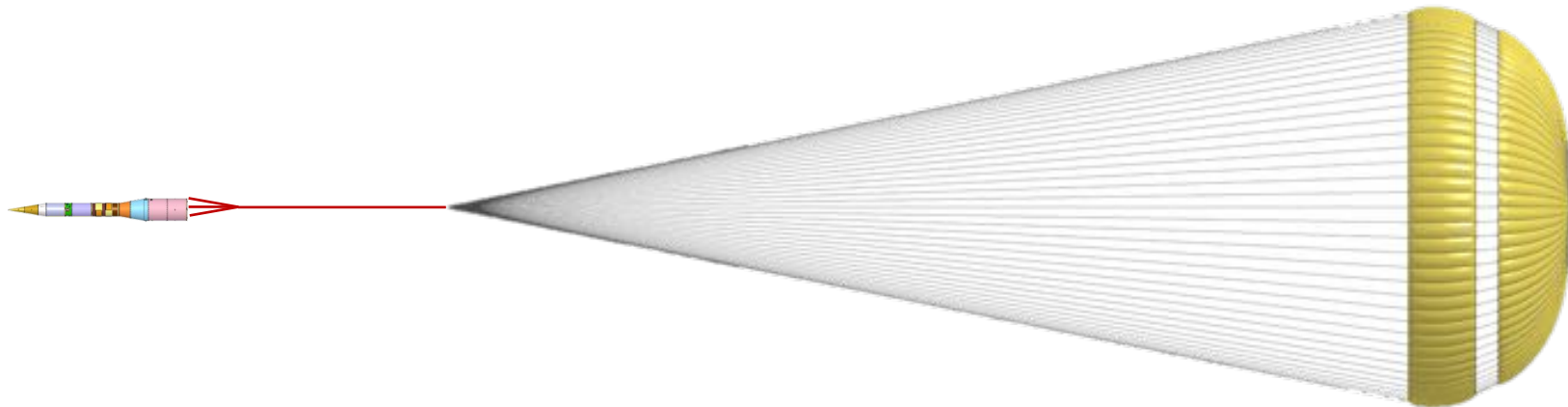
## Challenges:

- Parachute performance depends on many variables  
(Mach number, geometry, leading body, fabric permeability, trailing distance etc)
- Little data on parachutes of this size and trailing distance at relevant Mach numbers behind a slender leading body

O'Farrell et al, 2017 IEEE Aerospace Conference,  
*Development of Models for Disk-Gap-Band Parachutes  
Deployed Supersonically in the Wake of a Slender Body*

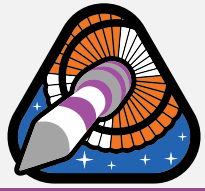
## Approach :

- Use models for MSL/M2020; use CFD to understand effect of leading body (blunt vs slender) & adjust



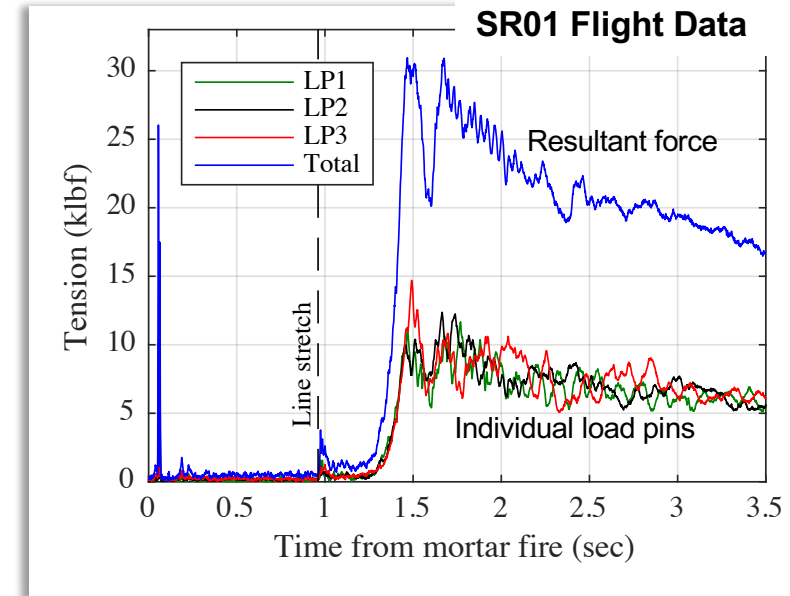


# Parachute Deployment and Inflation



ASPIRE

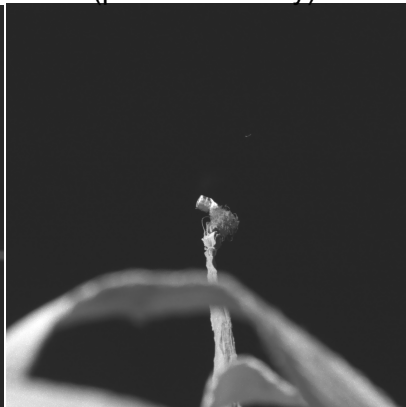
- Parachute deployment and inflation are highly dynamic events
- Time(s) :
  - Mortar fire (initiation) to line stretch:  $\sim 1.0$  s
  - Line stretch to Full Inflation:  $\sim 0.5$  s
- Tension measurements from load pins  
(Parachute force = tension + payload mass  $\times$  acceleration)
- Full inflation followed by a collapse/rebound and a second peak
- Peak Aerodynamic Load is a quantity of interest.



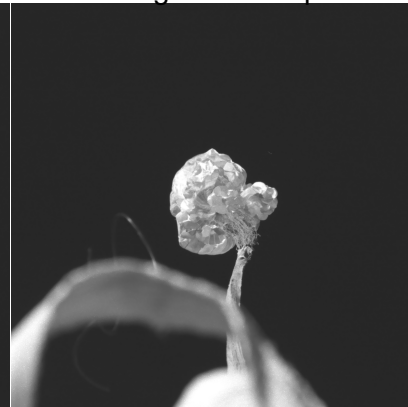
Parachute pack sailing away from the payload



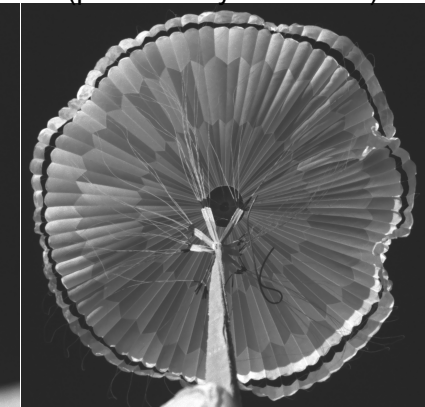
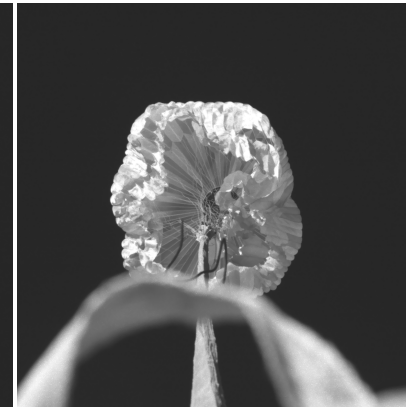
Line Stretch  
(pack 45 m away)



Parachute begins to emerge from the pack

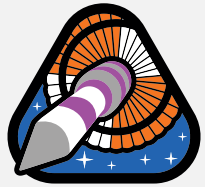


Parachute Fully Inflated  
(peak aerodynamic load)



Images from the on-board high-speed camera

# Parachute Deployment and Inflation



ASPIRE

- Peak Aerodynamic Load during SR01 : 32.4 k lbf (144.07 kN)

(Pre-flight prediction 35,000 lbf)

- Inflation load indicator  $F_{peak} = k_p(2q_{\infty}S_p)$

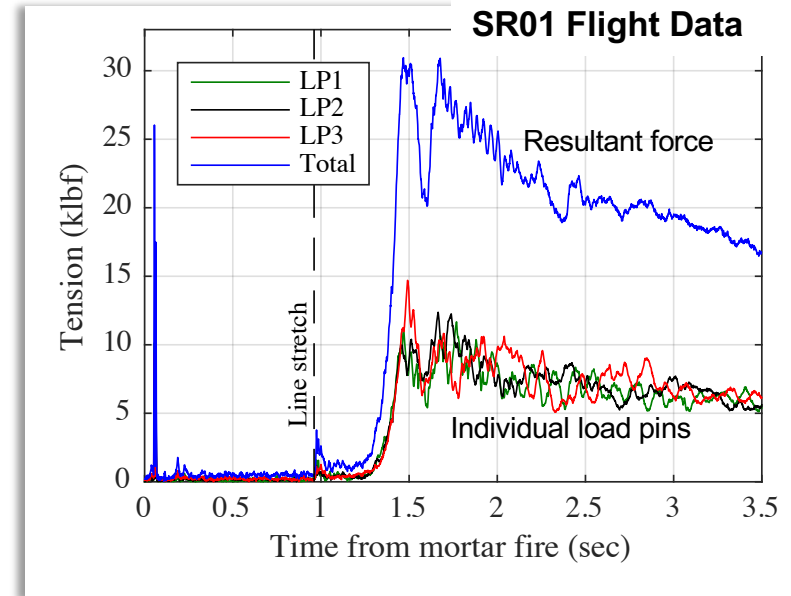
$S_p$ : Parachute Projected Area  
 $q_{\infty}$ : Freestream dyn. press.  
 $k_p$ : Inflation constant

Pre-flight range for  $k_p$   
 (informed using CFD)

0.70 - 0.90

Test	dyn. press.	Inflation Load	$k_p$
SR01	495 Pa	32,400 lbf	0.77
SR02	626 Pa	55,800 lbf	0.78
SR03	1020 Pa	67,400 lbf	0.76
MSL		35,000 lbf	0.83

$k_p$  consistent across the three flights;  
 towards the lower end of the pre-flight prediction.

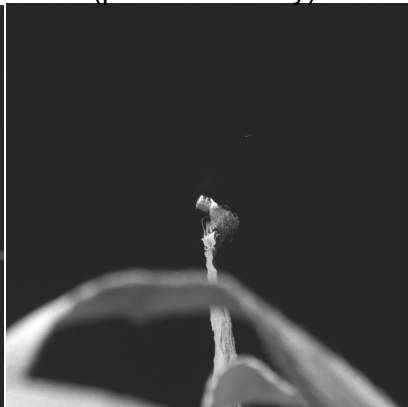


Way, 2018 IEEE Aerospace Conference,  
 A Momentum-Based Indicator for Predicting the  
 Peak Opening Load of Supersonic Parachutes

Parachute pack sailing  
 away from the payload



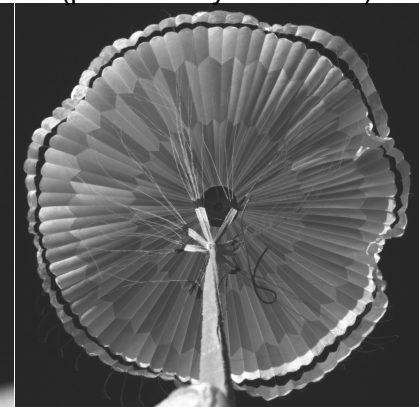
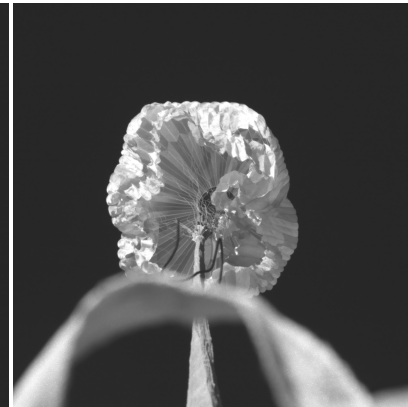
Line Stretch  
 (pack 45 m away)



Parachute begins to  
 emerge from the pack

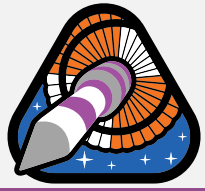


Parachute Fully Inflated  
 (peak aerodynamic load)



Images from the on-board high-speed camera

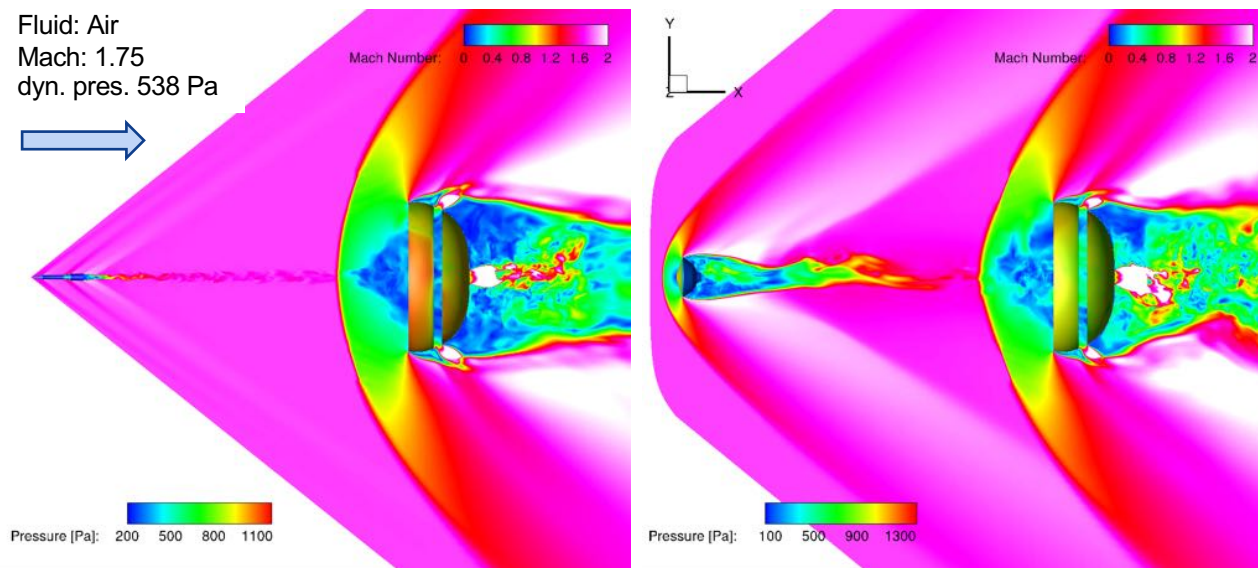
# Parachute Drag Model Development



ASPIRE

- Parachute drag model: Variation of  $C_d$  with freestream Mach number
- Very little flight test data for supersonic parachutes behind slender bodies and these conditions.
- MSL parachute drag model (behind blunt capsule) was modified to yield the ASPIRE parachute drag model.
- The modifications were informed by (limited) flight and wind tunnel tests, and numerical simulations.

Fluid: Air  
Mach: 1.75  
dyn. pres. 538 Pa



*Image shows contours of Mach number on the cut-plane,  
contours of pressure on the leading body and parachute interior*

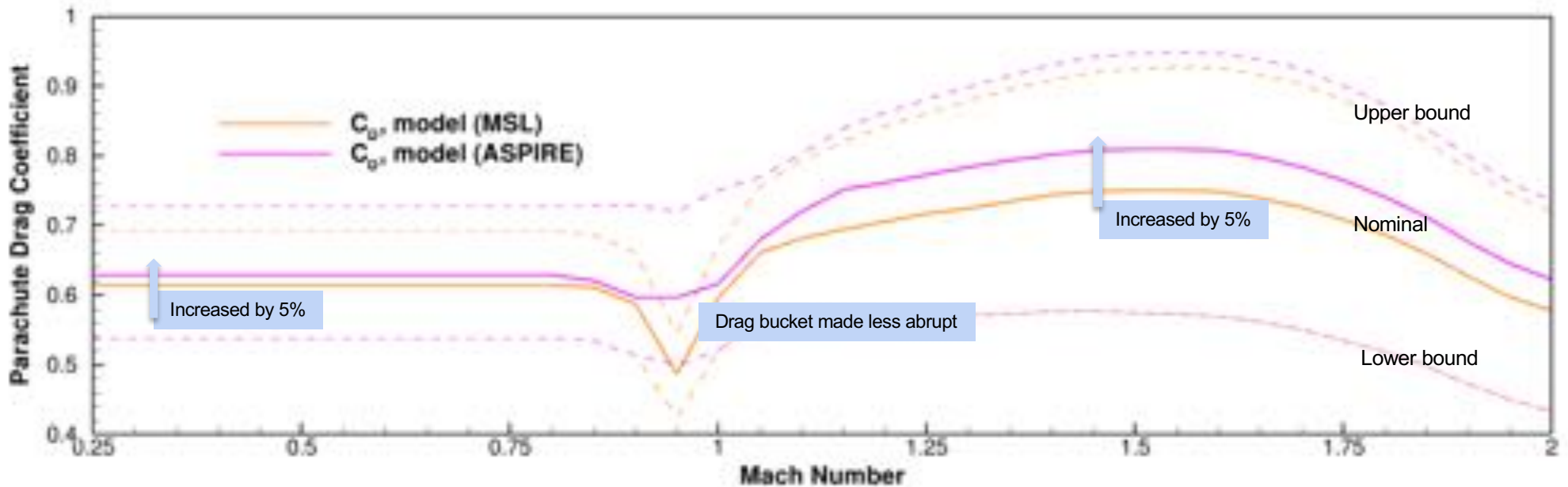
Q. What is the effect of leading body on the drag of a rigid, simplified parachute ?

- Highly unsteady flow and aerodynamic forces
- Wake-parachute bow shock interaction stronger behind blunt body
- Mean parachute force behind the slender body is higher
- Consistent with a larger wake and deficit behind blunt body

# Pre-Flight Parachute Drag Model



ASPIRE



- MSL parachute drag model was modified to yield the ASPIRE parachute drag model.

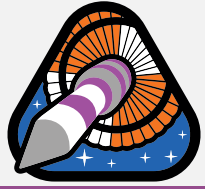
Subsonic: Increased nominal drag performance and the high margin; retained the low margin

Supersonic: Increased nominal drag performance and the high margin; retained the low margin

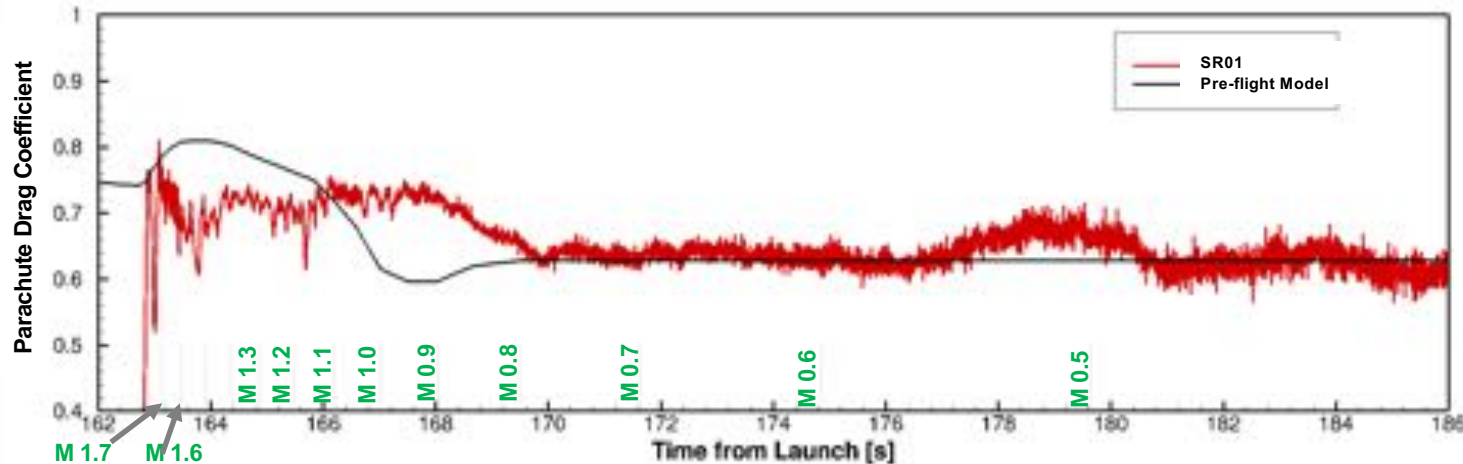
Transonic: reduced the steep reduction at near-sonic conditions; blended the subsonic and supersonic drag curves

- The ASPIRE drag model (and the bounds) was used in the flight mechanics simulations, and to help design the flight tests.

# Reconstructed Parachute Drag



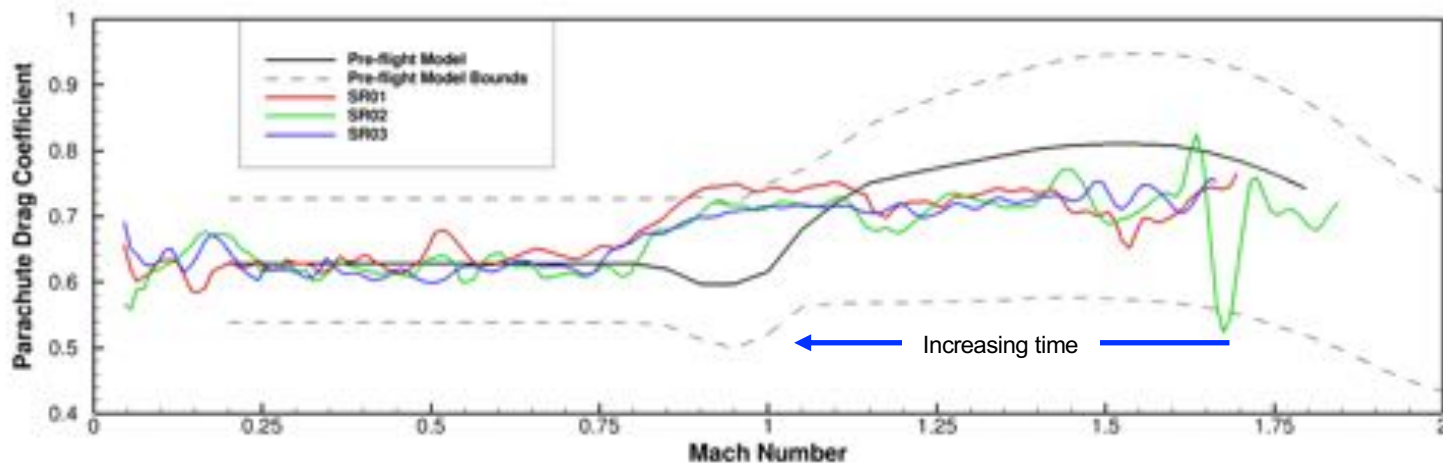
ASPIRE



Good Agreement below Mach 0.75

Over-prediction above Mach 1.15

Test Data does not show a transonic drag reduction



Consistent drag performance across three flights

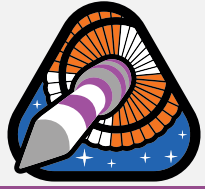
Pre-flight bounds capture all the data from three flights (about 90 min of flight data)

Flight data indicates a near-constant subsonic drag, and a near-constant supersonic drag

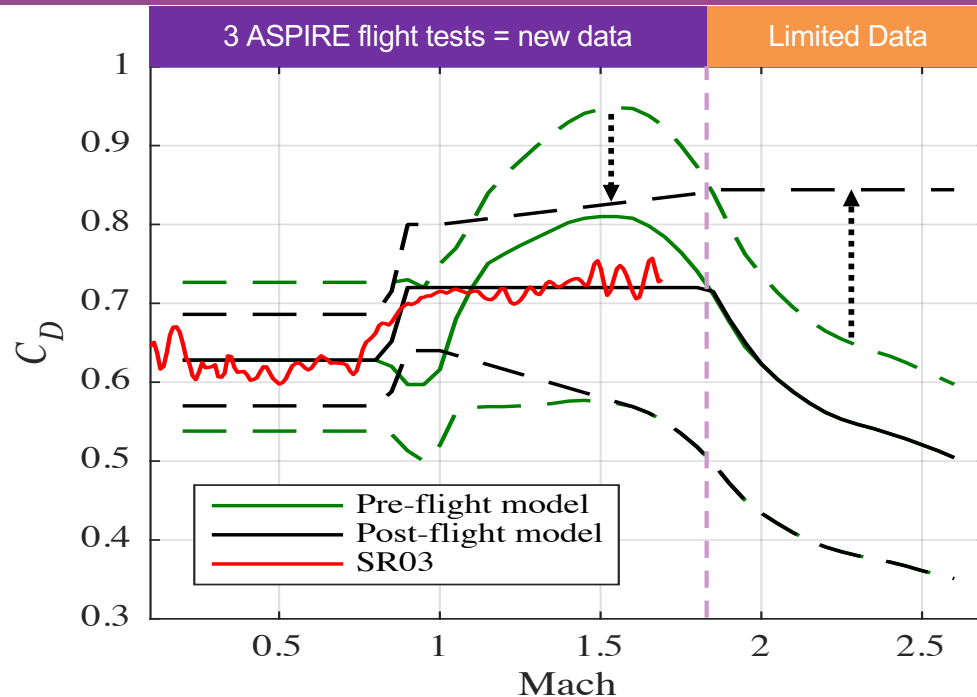
Post-flight analysis indicates that the transonic drag decrease is a blunt leading body effect.



# Updated Slender Body Parachute Drag Model



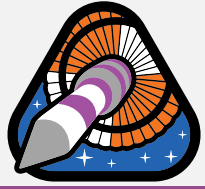
ASPIRE



- $M < 1.8$ : Takes advantage of the ASPIRE flight tests
- $M > 1.8$ : *single* wind tunnel test + *single* flight test (shorter trailing distances; both show a reduction in parachute drag)

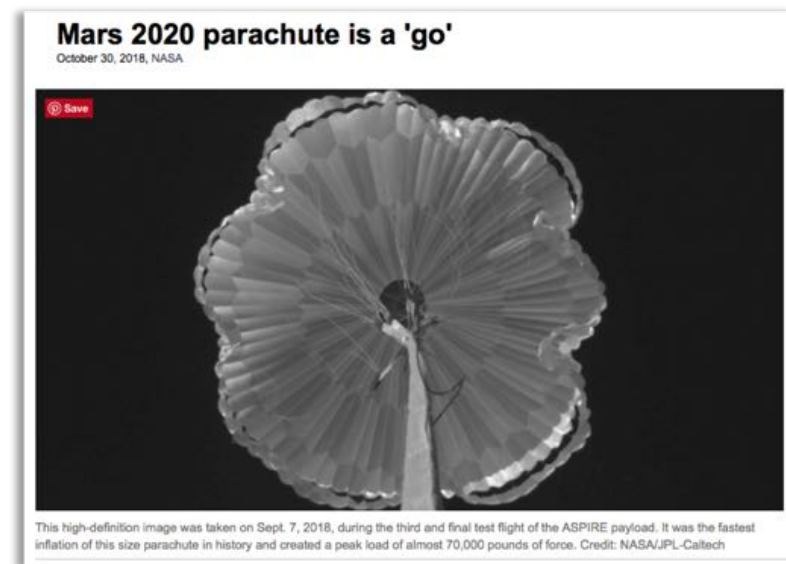
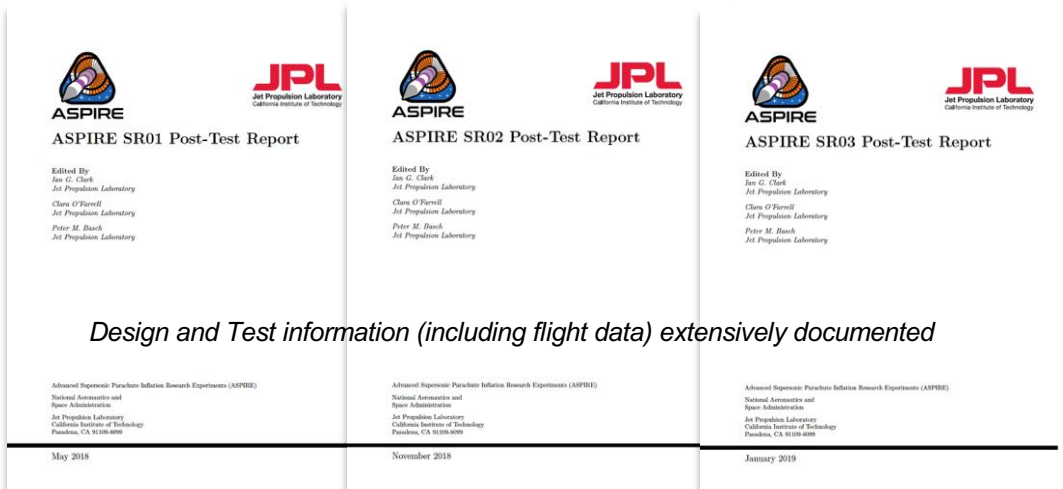
- Nominal Model:
  - Constant subsonic  $C_d$  ( $M < 0.75$ ); unchanged from pre-flight model
  - Constant supersonic  $C_d$  ( $0.8 < M < 1.8$ ); based on the flight tests
  - Revert to pre-flight  $C_d$  ( $M > 1.8$ ); absence of new data
- Uncertainties:
  - Reduced subsonic uncertainty bounds ( $M < 0.8$ ); based on the ASPIRE flight tests
  - Reduced supersonic uncertainty bounds ( $0.8 < M < 1.8$ )
  - Increased upper bound at higher Mach numbers ; no new data + account for possibility of near-constant drag coefficient

# Conclusions



ASPIRE

- ASPIRE project was launched to test supersonic parachutes at Mars relevant conditions first full-scale supersonic tests of parachute in over 40 years.
- ASPIRE established a framework for testing full-scale parachutes.
- Through the three flight tests, ASPIRE 'certified' a parachute for upcoming Mars2020 mission and broke records (fastest inflation, highest load for a parachute this size).
- CFD simulations help generate aerodynamic models and design the flight test; Pre-flight payload and parachute models/predictions compare well to the flight data. CFD simulations (pre- and post-test) help investigate effect of leading body on parachute performance.
- Proposed an updated parachute drag model behind slender bodies.
- Established a process to develop aerodynamic models and to design flight tests for future parachute testing.

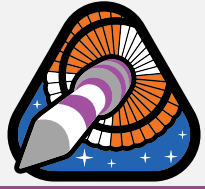


# Backup



ASPIRE

# Test Articles



ASPIRE

Two candidate designs for Mars2020:

- A build-to-print 21.5-m MSL DGB (tested to 35 klpf on SR01)
- Strengthened version of MSL DGB (identical geometry, stronger materials)

## MSL Built-to-Print

4000 lb Kevlar Web

1.3 oz/yd<sup>2</sup> Polyester  
(60 pli)

1.1 oz/yd<sup>2</sup> Nylon  
(42 pli, 100 cfm)

2500 lb Kevlar Web

2100 lb Technora cord

Mass: 58 kg  
Nominal diameter: 21.31 m  
Geometric porosity: 12.8%

## M2020 Strengthened

6000 lb Kevlar Web

1.9 oz/yd<sup>2</sup> Nylon  
(110 pli, 90 cfm)

2400 lb Kevlar Web

3200 lb Technora cord

Mass: 88 kg  
Nominal diameter: 21.45 m  
Geometric porosity: 12.8%